

ASSESSMENT OF THE ONERA/DLR NUMERICAL AEROELASTICS PREDICTION CAPABILITIES ON THE HIRENASD CONFIGURATION

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Abstract: The present paper deals with steady and unsteady aeroelastic simulation results obtained on the High Reynolds Number Aero-Structural Dynamics (HIRENASD) wind tunnel configuration [1], selected as common test case in the numerical aeroelasticity ONERA/DLR cooperation project “NLAS2”. In order to assess the aeroelastic prediction capabilities of the flow solvers elsA (ONERA) and TAU (DLR), 3 types of simulations have been realized: static coupling, harmonic forced motion and dynamic coupling. The set-up of the numerical simulations as well as comparisons with experimental data are presented for selected test cases.

1 INTRODUCTION AND WIND TUNNEL MODEL SET-UP

The HIRENASD experiments have been conducted by the RWTH Aachen University at the cryogenic European Transonic Wind tunnel (ETW) with funding from the German Research Foundation (DFG). The ETW enables the setting of static pressure, Reynolds and Mach number independently of each other using liquid nitrogen. Data were collected for Reynolds numbers in the range from 7 to 73 million and Mach numbers from 0.7 to 0.88. The main objectives were the collection of comprehensive aeroelastic results for the validation of simulation programs and to provide insight into the flow physics at transonic conditions, especially at high Reynolds numbers, realistic for civil transport aircraft.

Figure 1 shows the HIRENASD project experimental set-up in the wind tunnel. The planform of the wing (shown in Figure 2) is comparable to those of typical transport aircraft (twice kinked trailing edge, sweep angle 34°), and comprises a supercritical BAC 3-11 airfoil, a fuselage substitute is mounted to separate the boundary layer developing on the wind tunnel ceiling from the wing. The deformation of the wing due to static and dynamic loading was measured using the optical 3D position measurement system picCOLOR. Acceleration sensors provided dynamic displacement information; forces and moments were measured using an elaborate wind tunnel balance. The excitation of the model in its structural resonance frequencies is enabled by a system of four piezo stacks that transmit forces at the wing root clamping section into the wing. A detailed description of the HIRENASD model and the measuring equipment can be found in [1].

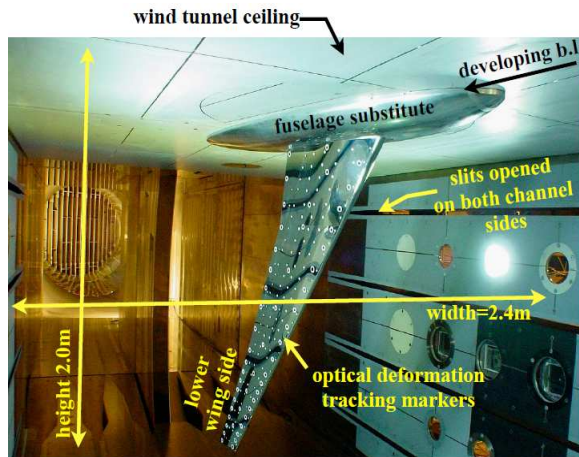


Figure 1 : HIRENASD experimental set-up in ETW

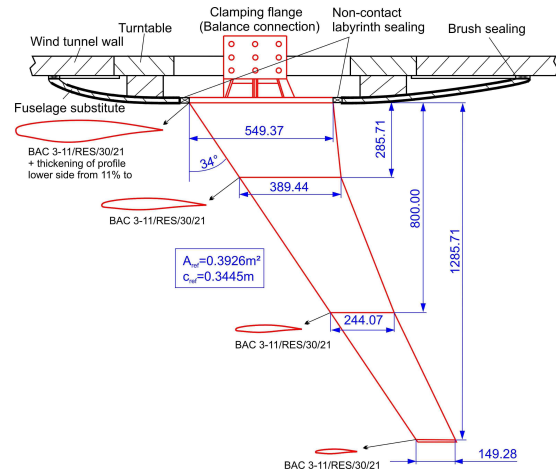


Figure 2 : Planform of the model

2 NUMERICAL MODELS USED FOR SIMULATIONS

In order to realize coupled aeroelastic simulations, both structural and aerodynamic models capable of describing the relevant physical aspects are required. The provided CFD mesh used for the elsA CFD simulations is a 45 blocks structured mesh composed of 3.5 millions nodes and 3,2 millions cells, whereas the TAU mesh is unstructured and consists of 8.8 millions nodes and 21 millions cells. The structured NASTRAN FE model is made of 200 000 nodes and 42000 CHEXA elements, and represents the wing and its wall clamping system. Figure 3 shows the structured CFD skin meshes and the FE model.

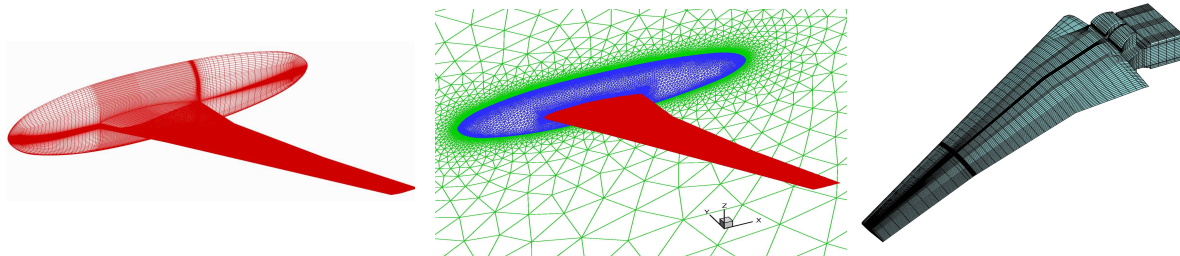


Figure 3 : Structured and unstructured CFD mesh for elsA and TAU, respectively, and structured FE

3 STEADY SIMULATIONS: STATIC FLUID-STRUCTURE INTERACTION

The provided structured CFD mesh is directly used by the elsA code. However, NASTRAN pre-processing steps on the FEM are needed to get data adapted to the “AEL” aeroelastic module of elsA: the reduced flexibility matrix and the mode shapes. Static coupling simulations have been carried out with the “reduced flexibility matrix” approach. Red dots on the Figure 4 represent the “fish bones” structural model, corresponding to “force” and “displacement” nodes of the reduced flexibility matrix.

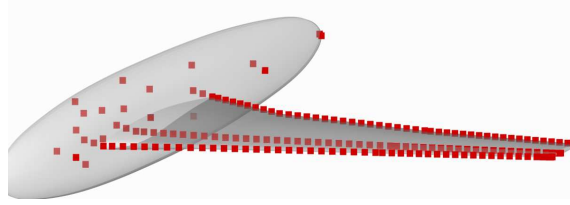


Figure 4 : Skin model and reduced flexibility matrix structural nodes

To perform coupled aeroelastic simulations with TAU, the PyCSM program which is a development of the DLR Institute of Aeroelasticity is used. This software, written in Python/NumPy, is capable of performing steady fluid-structure interaction as well as forced motion simulations. The interface to TAU is established using the TAU-Python modules. The transfer of aerodynamic to structural loads as well as the interpolation of displacements of the structural to the aerodynamic nodes is done by a coupling matrix which is in turn built of radial basis functions [3]. The DLR coupling chain is sketched schematically in Figure 5.

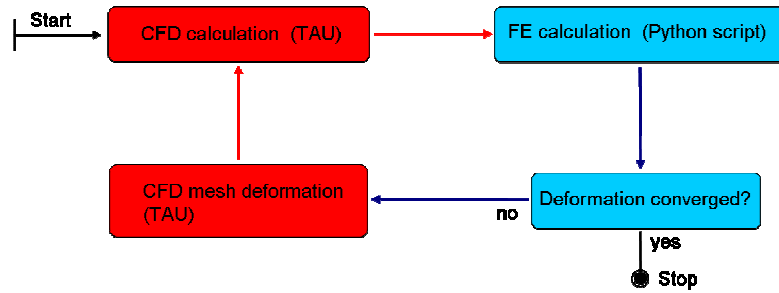


Figure 5 : Sketch of the steady coupling simulation chain

The coupling chain solves for the steady structural equation of motion for the generalized displacements:

$$\Omega^2 q = (H\Phi_s)^T f_a$$

Where Ω denotes the structural eigenvalues, q the generalized displacements, H the interpolation matrix, and Φ the mode shapes. For the steady fluid-structure-interaction simulations, the lowest 20 eigenvalues and mode shapes were used as modal basis. Since the HIRENASD wind tunnel model is designed for operating at very low temperatures (down to 110K), highly tenacious steel was used resulting in comparatively high elastic eigenfrequencies. The frequencies of the five lowest elastic modes are given in Table 1. Due to the comparatively high stiffness of the entire model setup, rather low elastic deformations were expected at the aeroelastic equilibrium and thus the modal approach (based on a linear deformation theory) is appropriate for the calculation of the deformation.

Mode shape	Type	Natural (in vacuo) frequency [Hz]
1	First bending	26.5
2	Second bending	86.0
3	First in-plane bending	156.9
4	Third bending	189.3
5	First torsion	272.9

Table 1: Five lowest mode shapes and corresponding natural frequencies

The main results presented here consist in comparisons between ONERA/DLR numerical results and experimental data. In order to compare the aeroelastic equilibrium shape with the jig-shape, “rigid” CFD simulations on the jig-shape, in the same aerodynamic conditions were first conducted. The elsA code reaches convergence after 1000 iterations for rigid CFD and static coupling simulations. The aerodynamic parameter of the steady simulations are given in Table 2, it corresponds to the HIRENASD experimental test case “196”.

Mach	0,8
Re	14×10^6
AoA	$0^\circ, 3^\circ$
q/E	$4,70 \times 10^{-7}$

Table 2: Aerodynamic simulation conditions for HIRENASD test case 196

The course of the residual and the lift, drag, and moment coefficient of the coupled simulation with TAU is depicted in Figure 6. The discontinuities in all plotted values arise from the coupling steps each time a new loop is done. In that case, steady aeroelastic equilibrium was reached after 3 coupling steps with the TAU code and 5 or 6 with the elsA code (cf. Figure 6)

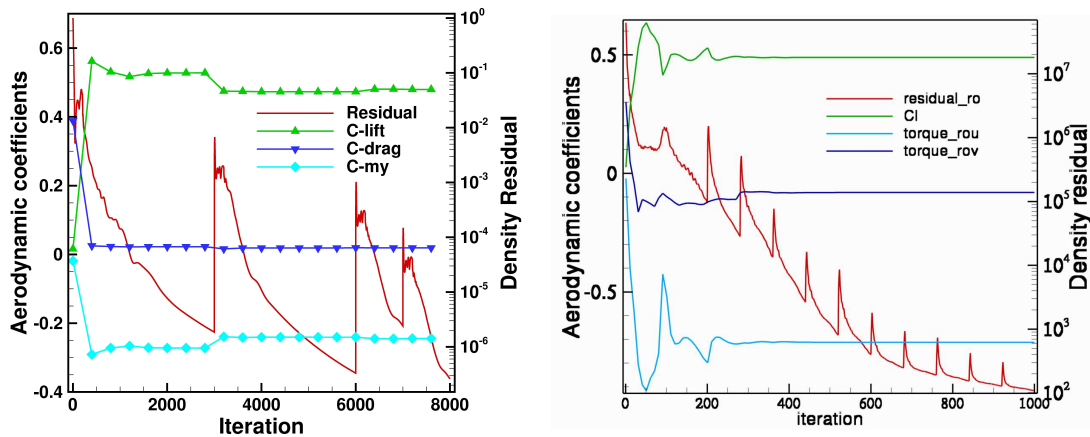


Figure 6: Residual and aerodynamic coefficients during coupling simulation – TAU (left) and elsA (right)

Figure 7 compares ONERA/DLR and experimental spanwise twist and bending evolutions, for the $AoA = 3^\circ$ configuration. However, experimental twist data are missing. Thus it is not possible to conclude on the most accurate twist prediction capacity between elsA and TAU results. The experimental deformations data are from regions not located exactly at the leading and trailing edge, but at some distance inwards (in chordwise direction). Thus the simulation data enfold the experimental ones as it can be observed on Figure 7.

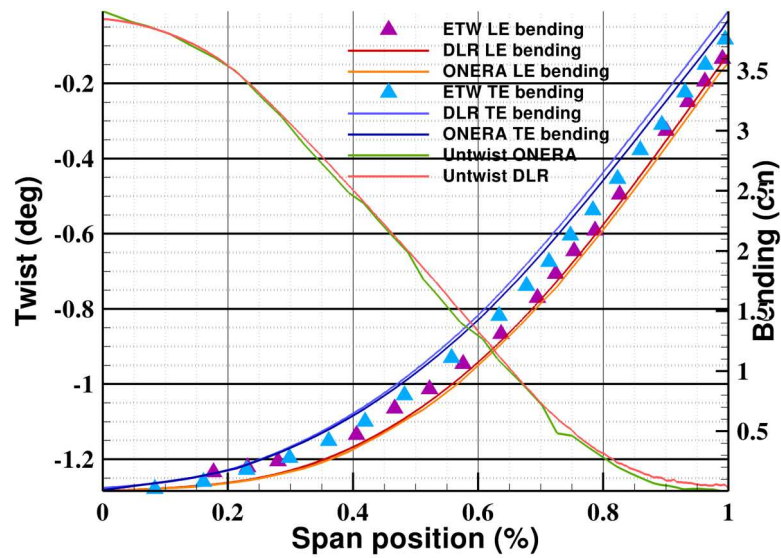


Figure 7 : Spanwise twist and bending – $M=0.8$ – $Re=14e6$ – $q/E=0.47e-6$ – $AoA=3^\circ$

A more detailed assessment of the ONERA and DLR results in terms of the steady flow field past the wing is obtained by a comparison of the C_p distribution at different spanwise locations. Additionally, the values of the simulated pressure coefficient can be compared to the experimental one. Figure 8 indicates the spanwise positions of the pressure sensors past the wing and represents comparisons between elsA, TAU and experimental results, for the $AoA = 3^\circ$ configuration. There is a comparatively good agreement between numerical and experimental results. However, TAU results show a slightly better agreement with the experimental values than the elsA ones: especially for the prediction of the shock in the wing tip area. In fact, the elsA code seems to predict a shock too strong in this area.

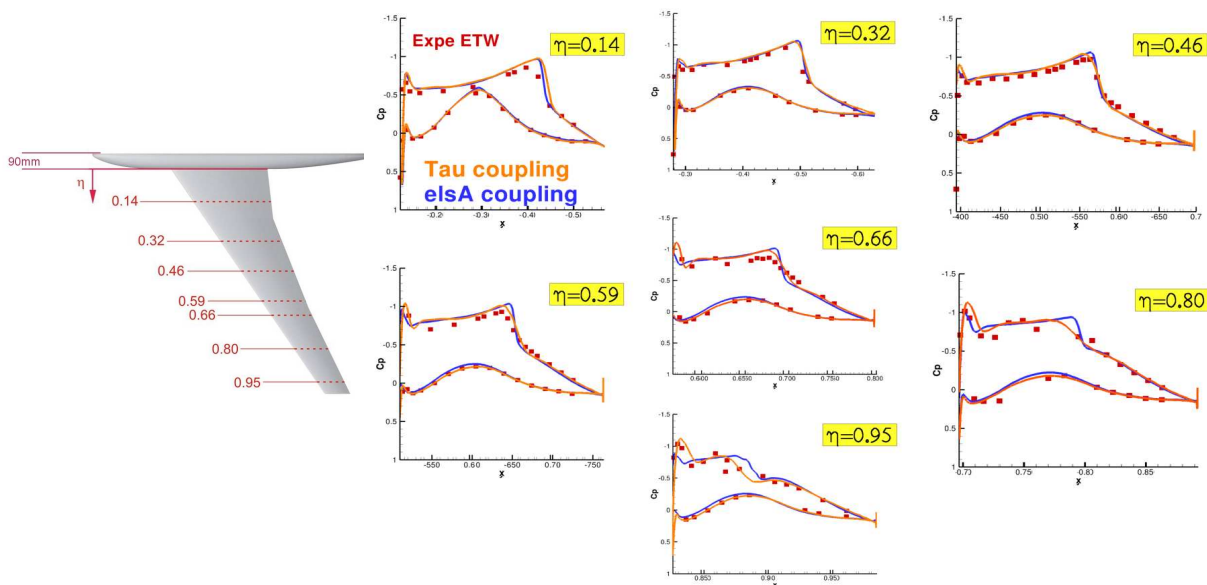


Figure 8 : C_p cuts location and steady C_p cuts for static coupling simulation elsA and TAU – case 196
 $M=0.8$ $AoA=3^\circ$

The most important flow solver parameters that were used for the static coupling simulations by elsA and TAU are denoted in Table 3.

Parameter	elsA setting	TAU setting
Inviscid flux scheme	JST central	JST central (scalar dissipation)
Multigrid cycle	2 levels (v-cycle)	3 levels (w+)
Number of iterations/coupling-step	80	1000 to 3000
Total number of iterations	1000	10 000
Convergence level	1.e-6	1.e-6

Table 3: Flow solver parameters of the steady coupling simulations

4 UNSTEADY SIMULATIONS: FORCED MOTION

4.1 Steady simulations as initial solution for the unsteady simulations

As first step for any unsteady forced motion simulation process, a static coupling simulation with the same aerodynamic conditions as the intended unsteady case must be performed. Initial, steady flow field and the deformed mesh are results of the corresponding static coupling simulation (made with the elsA AEL «flexibility matrix» approach by ONERA and the PyCSM program by DLR). They are both used to initialize the forced motion simulation. The unsteady results presented in the following correspond to the HIRENASD experimental test case 179, it was chosen due to the good quality of the associated experimental data (both steady and unsteady). The aerodynamic parameters of the steady initial simulation are given in Table 4.

Mach	0,8
Re	$6,9 \times 10^6$
AoA	1,5°
q/E	$2,2 \times 10^{-7}$

Table 4: Aerodynamic simulation conditions for HIRENASD test case 197

Figure 9 shows the steady pressure coefficient of elsA, TAU, and the corresponding experimental results. A very good agreement is globally achieved. However, the shock in the inboard and mid-span region is predicted too much downstream by numerical results.

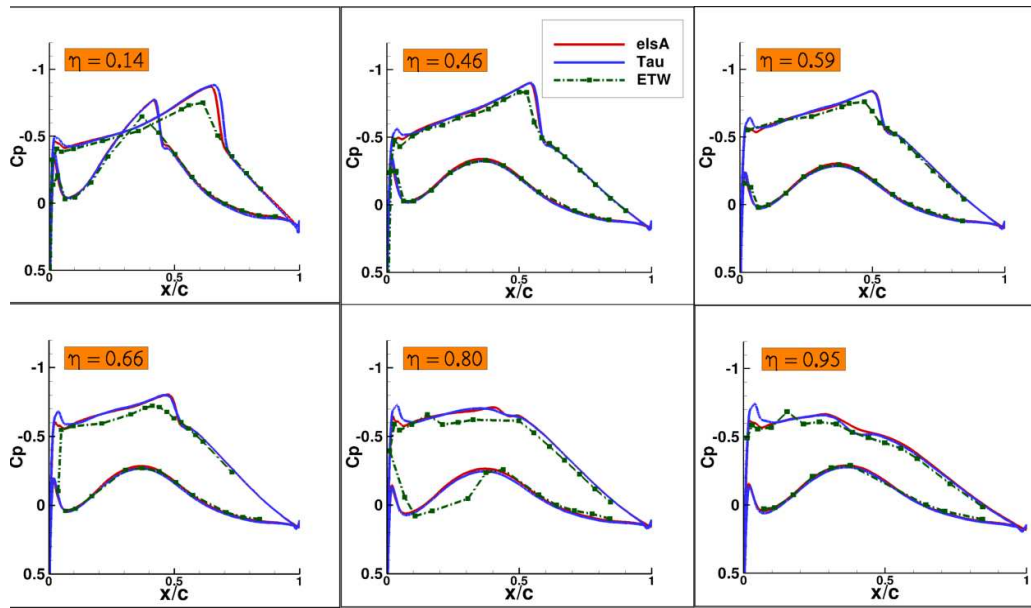


Figure 9 : Steady Cp cuts – elsA, TAU and experimental values – case 179 – $M=0.8$ $AoA=1.5^\circ$

4.2 Unsteady simulations

The HIRENASD unsteady test case 179 consists in a forced elastic vibration of the wing according to the second bending mode, the natural in vacuo frequency of this mode shape is 86 Hz. The frequency that was used for the simulations is 78.9Hz, this value was obtained from the corresponding experimental data.

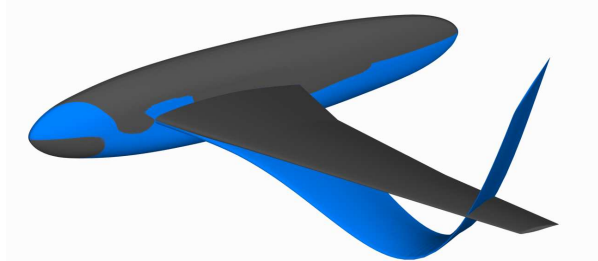


Figure 10 : Jig shape and 2nd bending mode shape

The structural damping of the model is unknown but expected to be very small, due to the material used which is very stiff. Thus damping was omitted for the modal analysis with NASTRAN and only real mode shapes were obtained and used for the forced motion simulations.

To enable a forced motion simulation, the structural mode shape is interpolated onto the aerodynamic mesh. The DLR approach therefore is to use the interpolation matrix denoted above. The so obtained mode shape on the aerodynamic mesh is deformed sinusoidally during the CFD simulation. A proper choice must be made for the unsteady time step and the number of inner iterations in order to assure the correct representation of the relevant physics of the flow field and good convergence. The experimental amplitude of the mode shape was 0.004 m, whereas the elsA simulations were done for an amplitude of 0.01m and the TAU ones for 0.0039 m. The reduced frequency of that case is 0.68. Both elsA and TAU solver used the Dual Time stepping (DTS) scheme for unsteady simulations. The settings are summarized in Table 5.

DTS Parameters	elsA	TAU
Iterations	256	480
Number of Periods	4	3
Number of Physical Time Steps per Period	64	160
Maximum Dual Iterations	20	250
Specified Minimum Residual	5/100	1/1000

Table 5: Settings for the Dual Time Stepping Scheme used for the unsteady forced motion simulations

In general, simulation results of the unsteady forced motion simulations exist as time series. From the aeroelastic point of view, two values are of great importance, which both apply to a description of the results in the frequency domain: the magnitude of the unsteady pressure coefficient and its phase, both related to the unsteady motion of the wing. These data can be obtained by a transfer function that relates the wing motion (actually the mode shape) to the aerodynamic “answer” of the wing.

A first unsteady simulation has been carried out using the Dual Time Stepping (DTS) technique. Figure 11 shows cuts of modulus and phase of the first harmonic C_p coefficient. Characteristic for all sections is the shock region in both the magnitude and the phase plot. An amplitude convergence study was conducted by DLR showing that with the chosen amplitude of 0.0039 m the linear range is held. This means that slightly smaller or larger amplitudes do not change the magnitude and the phase angle considerably. Modulus are very similar between elsA and TAU results, but in the tip region. Phase curves are very similar spanwise, knowing that the wing root cut cannot give consistent phase values. Numerical modulus peaks amplitudes in the shock region are very comparable to experimental ones. However, the peaks locations are slightly downstream the experimental ones: this is linked to the steady shock location prediction error (already mentioned). Both numerical modulus levels results in the upstream shock region are under-estimated in comparison with experimental results.

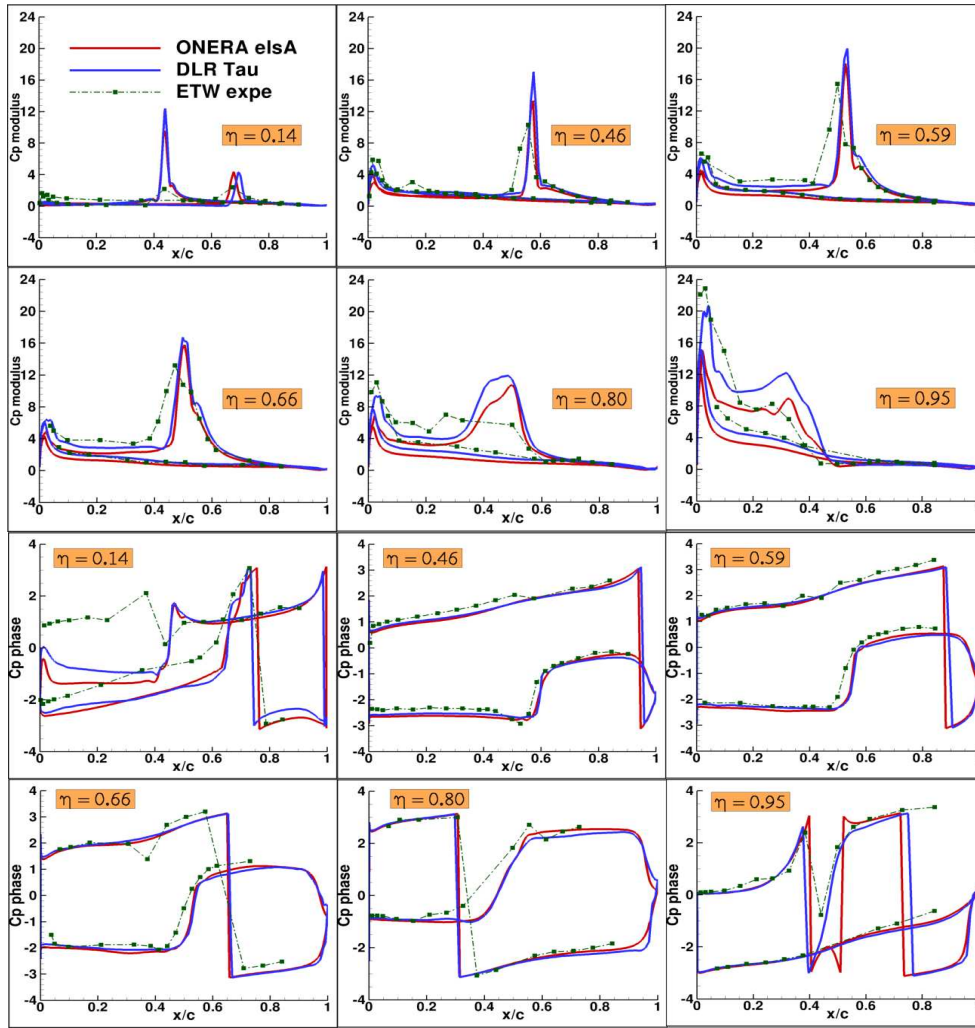


Figure 11 : 1st harmonic Cp modulus and phase spanwise Cp cuts – elsA, TAU and Expe - case 179 – $M=0.8$ $AoA=1.5^\circ$

The Time Spectral Method (TSM) [4] technique has also been used to realize the same forced motion simulation, in order to assess the computational time cost gain that could be reached on this “external flow” configuration. A one-harmonic TSM simulation was conducted with the elsA code. Results are plotted on Figure 12. A very good agreement is obtained in comparison with the reference elsA DTS unsteady simulation, but in the tip region. The computational time cost gain obtained is close to a 6 factor.

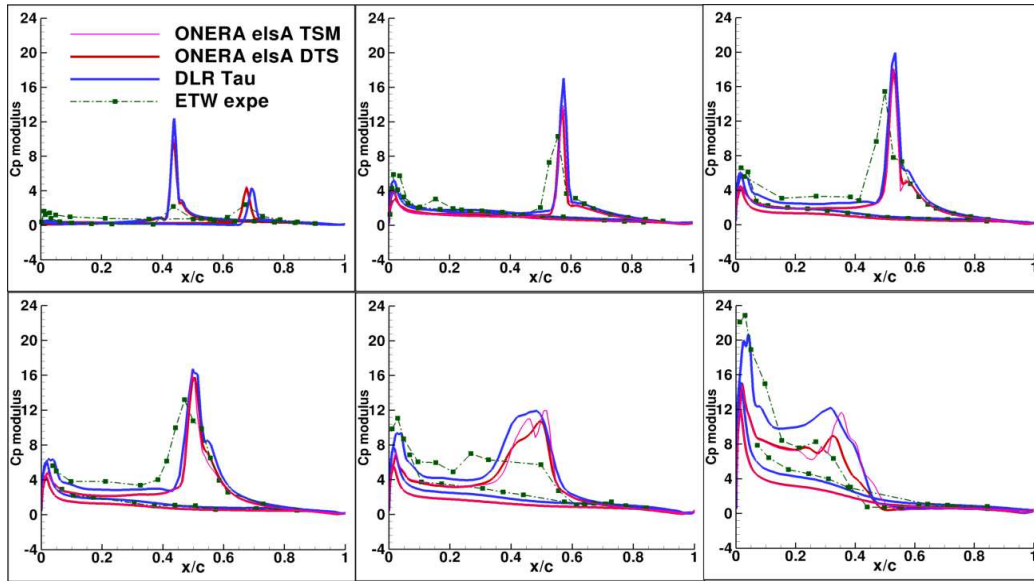


Figure 12 : 1st harmonic Cp modulus and phase spanwise Cp cuts with elsA TSM simulation results – POL 179 – M=0.8 AoA= 1.50

5 UNSTEADY SIMULATIONS: DYNAMIC COUPLING

This dynamic coupling simulation consists in simulating the free time response of the wing structure in a transonic flow, excited with an initial velocity.

<i>Aerodynamic conditions</i>	
Mach	0,8
Re	35x10⁶
AoA	0,0°
q/E	3,4x10⁻⁷

Table 6 : Aerodynamic condition for dynamic coupling simulation

This is a “strong coupling” technique which uses a modal approach to represent the structure dynamics. Only the 6th modes have been used. The initial velocity condition is made giving different initial velocities value on each mode. The first bending mode is excited with higher amplitude than any other mode. The purpose is to excite all the modes together and to analyze their damping behavior. Figure 13 represents the generalized coordinates time history signals. The red curve corresponds to the first bending mode generalized coordinate.

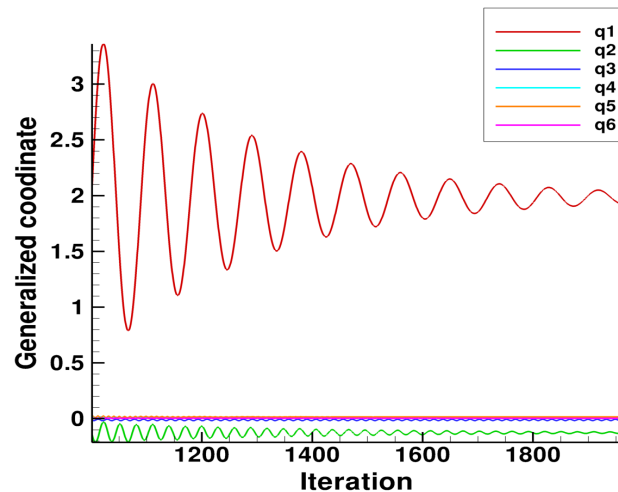


Figure 13 : Time history signals of generalized coordinates

As for “forced motion simulation”, this simulation has to be initialized using the resulting flow field and deformed mesh from the corresponding static coupling simulation. In that case, it has been needed to conduct a static coupling simulation with a modal approach and with the same modal basis as the dynamic coupling simulation.

<i>Simulation parameters (elsA)</i>	
Iterations (physical)	960
Approximated number of periods of the first mode	10
Number of physical time step per first mode period	96
Approximated physical time step per sixth mode period	8
Number of structural dynamic solving iterations (per physical iteration)	3
Maximum Dual Iterations (per structural dynamic solving iteration)	10
Minimum residual to reach	5/100

Table 7 : Numerical parameter for dynamic coupling simulation

A frequency analysis of the generalized coordinates time history signals plotted above (Figure 13), gives the aeroelastic frequency and damping coefficients of each mode. Comparisons are only made between elsA and RWTH (Aachen University) numerical results (SOFIA code). Figure 14 indicates that for the first aeroelastic mode (1st bending) the frequency obtained is 29Hz and the damping coefficient is 4.8%, which seems to be consistent with the RWTH results (28,8Hz and 4,4%). For the 5th mode (1st torsion), the calculated frequency is 263Hz whereas RWTH results give 271Hz, knowing that the eigen-frequency considered was around 273Hz. Concerning the damping coefficient elsA gives 1% whereas SOFIA gets 0.5%. However, those noticeable deviations on the 5th mode results cannot be used to draw any conclusion. Indeed, there is a lack of information about the RWTH simulation process that may explain these deviations.

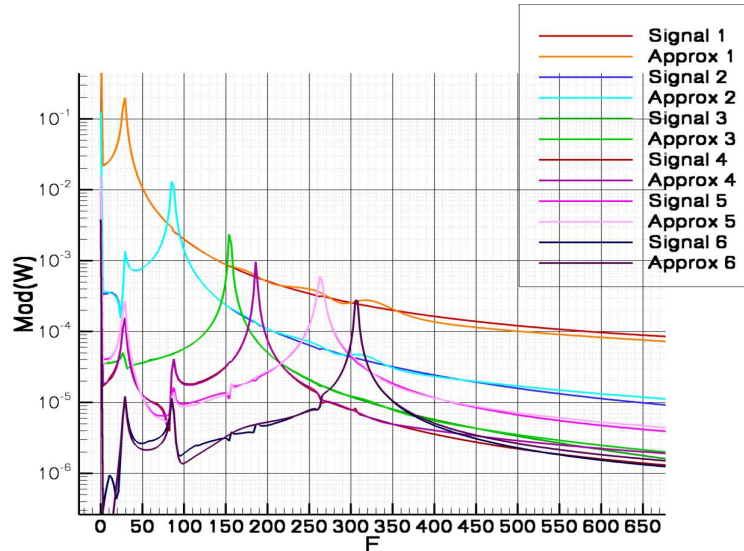


Figure 14 : FFT modulus of each generalized coordinate signal and approximation signal

6 CONCLUSION

This study has permitted to test the various capabilities of the TAU code and the elsA AEL module on the wing-body HIRENASD configuration. The corresponding experimental set up is a newly created aeroelastic experimental database which contains realistic flight conditions results. Thus, experimental static deformations as dynamic vibrations data could be used for interesting numerical comparisons. The 3 main types of simulations carried out are: static coupling, forced motion and dynamic coupling simulations.

Concerning static coupling simulations, good results have been achieved on bending deformation, comparing numerical (ONERA/DLR) and experimental results.

elsA forced motion simulations with DTS (time integration scheme) give rather good results in comparison with TAU and experimental data. elsA TSM simulation results are very similar to DTS ones, but in the tip region. This technique allows to get a reduction of a 6 factor on the computational time cost, with the drawback of memory resources increase (factor 3 for a one-harmonic TSM simulation).

The elsA dynamic coupling simulation has given satisfactory results for the 1st aeroelastic bending mode, in terms of frequency and damping coefficient. Results for the 5th mode (1st torsion mode) look not as good in comparison with RWTH ones. Investigations are needed, especially about the parameters of the corresponding RWTH simulation.

7 REFERECES

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